COMPUTATIONAL MODEL OF HUMAN & SYSTEM DYNAMICS IN FREE FLIGHT: STUDIES IN DISTRIBUTED CONTROL TECHNOLOGIES

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This paper presents a set of studies in full mission simulation and the development of a predictive computational model of human performance in control of complex airspace operations. NASA and the FAA have initiated programs of research and development to provide flight crew, airline operations and air traffic managers with automation aids to increase capacity in en route and terminal area to support the goals of safe, flexible, predictable and efficient operations. In support of these developments, we present a computational model to aid design that includes representation of multiple cognitive agents (both human operators and intelligent aiding systems). The demands of air traffic mnagement require representation of many intelligent agents sharing world-models, coordinating action/intention, and scheduling goals and actions in a potentially unpredictable world of operations. The operator-model structure includes attention functions, action priority, and situation assessment. The cognitive model has been expanded to include working memory operations including retrieval from long-term store, and interference. The operator's activity structures have been developed to provide for anticipation (knowledge of the intention and action of remote operators), and to respond to failures of the system and other operators in the system in situation-specific paradigms. System stability and operator actions can be predicted by using the model. The model's predictive accuracy was verified using the full-mission simulation data of commercial flight deck operations with advanced air traffic management techniques.

INTRODUCTION

The world community of aviation operations is engaged in a vast, system-wide experiment in human/system integration. The nature of this change is to relax restrictions in air transport operations wherever it is feasible. The relaxation includes schedule control, route control, and, potentially, separation authority in some phases of, for example aircraft self-separation in enroute and oceanic operations. The process of relaxation of constraints is motivated by studies that suggest that reduction in schedule and route constraints (calculated in U.S. National Airspace (NAS) operations) could save the operator as much as 3.5 Billion U.S. dollars annually (Coularis and Dorsky, T 1995). This process of relaxation of constraints is made possible by an assumed improvement in navigational precision and by improvements in communications (global positioning systems and satellite data link capability). In the U.S., this process of relaxation has been termed "Free Flight" (RTCA 1996).

Implications for Human Performance

The consistent result of the relaxation of system constraints is to change and challenge human performance in that system in two dimensions. First, as more decisions are made available to people other than the air traffic service providers the decision-making process becomes distributed. Second, by the very fact that the concept of operations suggests flexible, dynamic operations human operators (pilots, air traffic controllers, and airline operations personnel) must monitor and predict any change in the distribution of authority and control that might result as a function of the airspace configuration, aircraft state or equipage, and other operational constraints. The operators are making decisions and sharing decisions not only about the management of the aircraft in the airspace, but also about the operating state of that airspace.

In order to safely and effectively describe the new process and procedures for this evolving concept, the human operator's performance must be clearly and consistently included in the design of the new operation and of any automation aiding that is proposed to help the operators in their distributed activities. The paper reports focused analyses and empirical studies to predict the consequences of the interaction between these advanced automation technologies and the human component in the ATM system.

REPRESENTATION OF HUMAN PERFORMANCE

In order to support these functions, we have developed a human/system model for advanced ATM operations that is a hybrid engineering control theoretic and cognitive performance model.

Engineering models of human performance have had a long and distinguished history if representing the human operator in continuous control of systems. (cf. McRuer and Jex, 1967, or Baron and Kleinman, 1969). In the optimal control theory of these models the human operator is assumed to act to observe a display of system state and to compare that display to an internal model of the system, represented as a Kalman estimator and predictor. The operator then chooses and action that will offset any observed error between current and desired system state and acts through his neuromotor processes, which include a noise and bandwidth limit, to effect the control. This methodology has been expanded to include discrete task (like decision making) Pattipati, Kleinman, and Eprath (1983), and to support a combination fo continuous and discrete control operations (Levison and Baron, 1997).

Traditional transfer function models are adequate to the inclusion of the operator as optimal controller with lag and noise components. However, because of the monitoring and supervisory role of the operator in the advanced ATM, the specific cognitive transfer function that the human operator provides also must to be considered. A model of human operator performance with explicit representation of the perceptual and decision-making processes has been developed (Corker and Smith 1993, Corker and Pisanich, 1995, Laughery and Corker 1997). The Man-Machine Interactive Design and Analysis System (MIDAS) serves as the basis of the advanced ATM performance developments addressed herein.

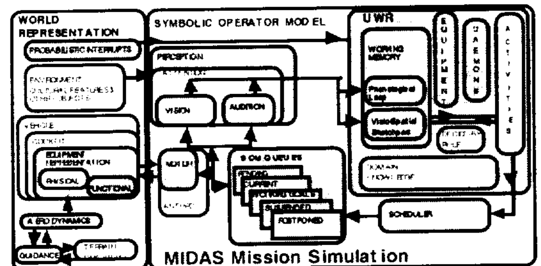

Figure 1: MIDAS Architecture for Human Representation in Complex Systems. Each of the modules represented in this figure is a functional model of human performance. In addition there are communication processes operating through information exchange buffers. The model elements are objects that are linked together into a closed-loop simulation of operator performance. This basic structure is replicated to account for multiple human operators in the system .

Human performance profiles arise as a function of the dynamic interplay among the following:

- the task demands,
- the characteristics of the operator reacting to those demands,
- the functions of the equipment with which the operator interacts, and
- the operational environment, the time course of uncontrolled events.

The MIDAS system attemtps to capture the salient aspects of the human cogntivie trandfer process by representing key functions for each operator in the system and then setting those operators in interaciton with each other. Fro a complete description of the MIDAS architecture please refer to Corker and Smith, 1993. Specific extensions and elaborationso fo that archtiecture are breifly described here.

Memory Representation. The role of the human operator in the ATM system places significant demands on his/her cognitive capacity, vigilance, and memory (Wickens et al., 1997). In order to capture the behaviors of the ATM practitioners we have modeled human memory structures as divided into long-term (knowledge) and working memory (short-term store). Working memory is the store that is susceptible to interference and loss in the ongoing task context[1] We have implemented working memory, described by Baddeley and Hitch (1974), as composed of a central control processor (of some limited capacity), an

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[1]. [Long-term loss would represent, for instance, a loss of skills or deep procedural memory of how to perform tasks. It is not considered to play a role in the scenarios under examination in this study.]

"articulatory loop" (temporary storage of speech-based information) and a "visuo-spatial scratch pad" (temporary storage of spatial information).

Attentional Control. Another capacity limit with implications for error formation and remediation in the human/automation integration task is attentional control and concurrent task performance. Distributed attention and attention switching refer to an operator's ability to perform multiple tasks simultaneously. Context and order sensitive effects require a scheduling and agenda management function that is provided in the MIDAS model for ATM

Activity Representation Tasks or activities available to an operator are contained in that operator's UWR and generate a majority of the simulation behavior. Each activity contains slots for attribute values, describing, e.g., preconditions, temporal or logical execution constraints, satisfaction conditions, estimated duration, priority, and resource requirements. A continuum of contingent or decision making behavior is also represented in MIDAS, following the skill, rule, knowledge-based distinction reported by Rasmussen (1983).

Task Scheduling: Activities which have their preconditions met, temporal/logical execution constraints satisfied, and required information retrieved from memory are queued and passed to a model of operator scheduling behavior. Based on the user's selected scheduling strategy (e.g., "workload balancing" or "time minimization"), activities are executed in priority order, subject to the availability of required resources. MIDAS contains support for parallel activity execution, the interruption of on-going activities by those of higher priority, and the resumption of interrupted activities. The specific design for this model of scheduling has been previously reported by Shankar (1991).

Expectation Rpresentation. In order to coordinate the activities of multiple human perofrmance models, or agents, we have defined an activity-type in which the activity of one agent may cause an anticipated activity on the part of another agent. These expectations are met, or not, weither through time, or an appropriate or inappropriate response to the expectation. Currently, expectations are tied to specfic activity types. Future development will inlcude representation in which agents may have full, or partial, knowledge of each others plans, goals and activities.

The human operators thus simulated, perform actions, communicate, make decisions and effect control as a function of simulaiton time moving forward, or contingent actions emrging in the world-model. The temproal resolution of operator aciton is currently set at 100 msec. The system has data collection mechanisms that allow collection of perfromance data at either the infdividual human operator level, at multiple operator levels, or, if desired, at the level of perfromance of the individual model elements.

REPRESENTATION OF AIR SPACE

Investigatig the critical elements of the national airspace evolution focuses on human/automation integraiton. Many issues must be resolved before what istermed "free flight" can reach a mature state of relaxed constraints in all airspace environments and incorporation of user preferences (RTCA, 1995). We have focused our early investigation on critical issues in air ground coordination and in distributed decision making.

The interaction among aircraft and controllers is proposed to occur at points in space around each aircraft called alert and protected zones (see Figure 2). These zones are to be used by an alerting system to monitor and advise the flight crew on conflicting traffic flying within these areas. In a cockpit-based system, the alerting system would warn the flight crew of any aircraft entering the alert zone. The crew could evaluate the situation and choose or negotiate a preferred deviation. If the intruding aircraft continued into the smaller warning zone, the crew would be advised to take immediate evasive action._

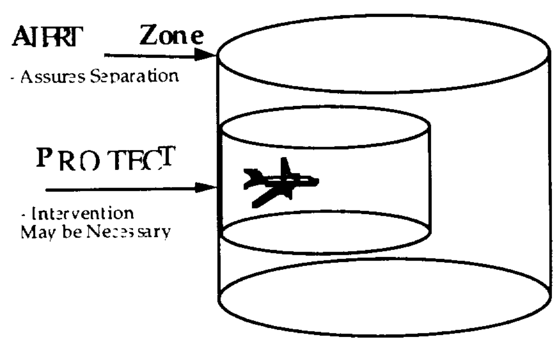
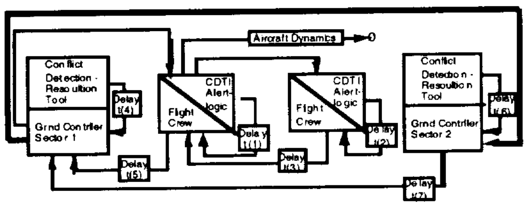


Figure 2. Schematic of proposed Free Flight protected and alert zones.

In addition to crew alerting, the air traffic service provider is also slated to be provided a ground-based conflict alerting and resolution system. An area of concern from the point of view of system stability is the interaction of the ground based alerting system with the aircraft based alerting system. In order to examine this decision process, we expanded the optimal control model structure (Baron and Kleinman, 1969) to account for multiple operators interacting with multiple decision aiding systems is illustrated in Figure 3.



Inner Loop A/C to A/C conflict alert and resoultion $t_a = t(1) + (t(2) + t(3)$
Middle Loop Controler to A/C conflict resolution $t_c = t(4) + t(5)$
Outer Loop Controller to Controller Coordination $T_C = t_c + t(6) + t(7)$
System Stability is compromised if T_C or $t_c < t_a$

Delays t(3), t(5), t(7) represent full-loop communication delays
Human automation loop delays t(1), t(2), t(4), t(6) are represented as serial in this formaulation that could also be considered as occuring independently and parallel. The dependent serial relation is the most conservative in terms of loop closure times.

Each of the active agents (flight crewsm and air traffic controllers) is represented by the MIDAS operator model described above. In the operational concept illustrated, there are two loops of alert and advisory information. The normal operational mode has the controller interacting with a conflict detection and resolution tool and providing positive guidance to and aircraft to initiate an avoidance maneuver, illustrated in the middle loop control. The optimal time to alert is a function that depends on the trade between conflict uncertainty and maneuver cost (Paeilli and Erzberger, 1997). It can be estimated to be on the order of 18 to 20 minutes to the point of closest approach of the aircraft. In some cases, there is the potential for the conflict to occur across adjacent sector boundaries. In this case an outer loop of communication among controllers is illustrated. The system also contains the inner loop of aircraft -to-aircraft alerting that is the focus of our simulation study. Full mission simulation data suggest that the time to initiate maneuver at strategic alerts is on the order of 7-9 minutes. A concern in this double loop is the convergence of inner and outer loop control time.

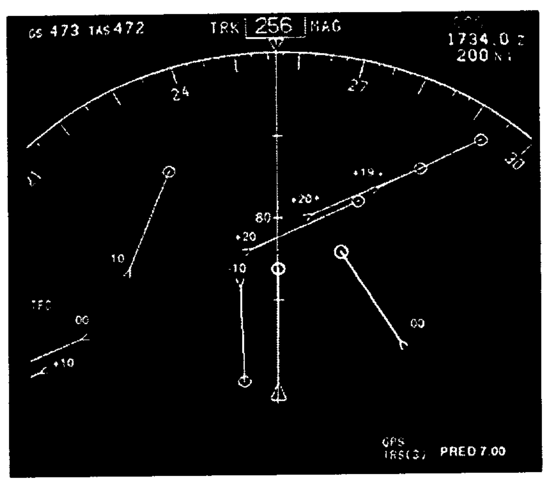
Two interactive elements of human autoimation interaction need to be characterized in order to predict the closed-loop behavior of this air-ground alerting system. First, the flight crews response to alert zone ransgression and their interaction with other aircraft to resolve the transgression must be identified. Second, the interaction of the ground-based alerting with and among controllers and then with the flight crew must be characterized. We wil describe a combination of full mission studies and computational analyses that are intended to identify the two interactive processes.

EMPIRICAL & COMPUTATIONAL STUDIES

The MIDAS model performance had previousy been demonstrated to be statistically indistinguishable form air-crew performance in the use of data-link communications and flight managment in descent. (Corker and Psianich, 1995). The model was exercised in this study to respond to an alert indictaing a convergnence of the subject aircraft and other aircraft. The models response time were compared to flight crews performing the same slef-spearation task.

Airborne Self-Separation Study

A full mission simulation for aircraft self-separation was performed using the NASA Ames Research Center 747-400 simulation facility (Sullivan and Soukup, 1996). (Please see Cashion et al. (1997) for details). Ten line qualified flight crews were provided a cockpit display of traffic information (CDTI) (Johnson et al. 1997). The CDTI provided own-ship and 120 nautical mile radius of oither aircraft (assuming and ADS-B psoition, altitiude and velocity broadcast). All aircraft in the scneario were assumed to be ADS-B equiped.



The flight crew was also provided alerting logic for conflict warning (Yang and Kuchar, 1997).with three level of situation alert before moving to the standard traffic collision avoidance systen (TCAS) alerting logic. The crews were provided a set of "rules-of-the-air" which assigned right of way to one aircratf or another as a function of the conflict geometry. The crews were exposed to two traffic density conditions (6-7 a/c = low density , 14-16 a/c= high density), and flew 4 encoutner scenarios in each condition. A variety of dependent measures were collected an examined int he study. We wil report one, manuever onset time, as a comparison between the MIDAS model in self-separation and the human pilots. While there were no significat differences in the dnsity manipulation. Cashion et al (1997) report: "for the lateral scenario type where the ownship has the right-of-way, a paired samples t-test was conducted on maneuver onset time. No effect was found for density, $\underline{t}(9) = -.72$, $\underline{p}$ = n.s" Maneuver onset time was defined as the time from which the intruder first appeared in the scenario to the onset of the first maneuver. A comparison of the model time to manuever onset campared to the mean high and low density of the flight crew also reveals no significant difference $t(18)= 3.20$ p= ns. Suggesting that the model beahvior and the crew behavior are similar in terms of the time to manuever response. This continues to reinforce our assertion that the MIDAS model is predtictive of air crew beahvior at a reasonable operational level.

Air Ground Integration

A seciond study in now underway in both computational analysis and empirical full mission simulation to investigate the impact of coordinated air-based and ground-based alerting logics. The MIDAS simulation has been expanded to include two sector controllers and emulaiton of conflict alerting logic on the ground as well as the current mutli-aircraft airborne crews and alerting logic. The empirical study will link controllers in the FAA William J. Hughes Technical Center.

The controllers and piltos will operate under two scenarios of separation authority one in which spearation is fundamentally ground-based and the other in which separation is fundamentally airborne. The MIDAS model will b used prior to simulation to attempt to predict air crew and controller behavior sequences and conflict resolution times in high and low aircraft density scneairos.

CONCLUSION

We continue to explore the extento which computational models of human peropfrmance can be used to predict air crew and controller behavior in advanced airpsace management practice. The results, to date are encouraging. There are however a number of issues that wil require further research. We have confidence that the MIDAS model predisct operational behavior at a course level of aircraft control. We have yet to explore the validation fo the micor-management of behavior and the contribution of individual behavior segements to the overall beahvior observed. We have not yet vlaidated the process of mutual expectation between air and ground based control authorities and have not explored off-niminal operaitons in simulation . These last issues will be the focus of the next studyt.

ACKNOWLEDGMENTS

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